THE YELLOWSTONE TALC MINE

By: Drew Morrison & Ericka Bartlett

1. INTRODUCTION

IMERYS' Yellowstone Talc Mine is the largest talc mine in North America, located 120 kilometers northwest of Yellowstone Park near Cameron, Montana. This geotechnical study was undertaken to determine if the relocation and construction of a new plant facility away from the pit edge could be delayed, resulting in significant short-term cost savings.

The focus of the geotechnical study was specifically on the geological rock type modeling and development of a stable slope design for Phase 5 (the next mining pushback), and verification of the design with monitoring and measuring of the achieved slope angles.

Stability criteria using static and pseudo-static analyses were established for overall slope angles with respect to the location of the pit facilities. The acceptable Factor of Safety (FOS) for static conditions was determined to be 1.3 or greater, with a Probability of Failure (POF) of 10% or less. The acceptable FOS for pseudo-static conditions is 1.2.

Once a design that achieved the desired slope criteria was established, slope monitoring systems were installed and the Phase 5 pushback proceeded in 2015. Slope verification of the Phase 5 pushback involved instrumentation of the subsurface, installation of slope RADAR, and geological mapping. Instrumentation of the subsurface included vibrating wire piezometers (VWP's), time domain reflectometry cables (TDR's) and inclinometers. Slope RADAR was installed to supplement the existing prism and GPS coverage. Geological mapping and slope measurements provided verification of the geological model, bench design, and overall slope angles. The design and geological model are updated during annual site visits.

The mining of the Phase 5 pushback commenced in 2015 and has excavated through the overlying volcanic units without significant signs of slope instability. The excavation is achieving the intent of its design thus far, deferring the expense of moving the mill processing facilities until a later date or future pushback.

2. GEOLOGICAL MODELING

The project area can be divided by rock type: the upper portion of the slope is comprised of volcanic units, and the lower portions of the slope consist of talc and dolomitic marble (referred to within as dolomite) bedrock. Generally, the upper slope volcanic units resemble homogeneous soils, while the bedrock units are jointed rock with an anisotropic character. Imerys modeled the talc ore body and Call & Nicholas Inc. (CNI) modeled the volcanic units.

Geological modeling is used to differentiate the volcanic units, as these materials exhibit variable geotechnical material properties. Major structure is modeled first to provide cross-cutting relationships and offset with respect to the volcanic units. Mapping data in conjunction with drill-hole intercepts provide the data for the volcanic units within the fault blocks.

Figure 1 is the geological model projected to April 2017 topography. The volcanic units consist of fill, (V2) rhyolite welded tuff, (V2) ash flow tuff, and (V3) a highly plastic debris flow unit. Bedrock units of dolomite and talc underlie the volcanic units. The Footwall Fault bounds the volcanic units to the northeast, while other faults offset the volcanic units into horst and graben blocks. A cross section view of the geological model at the Yellowstone Talc Mine is shown in Figure 2.

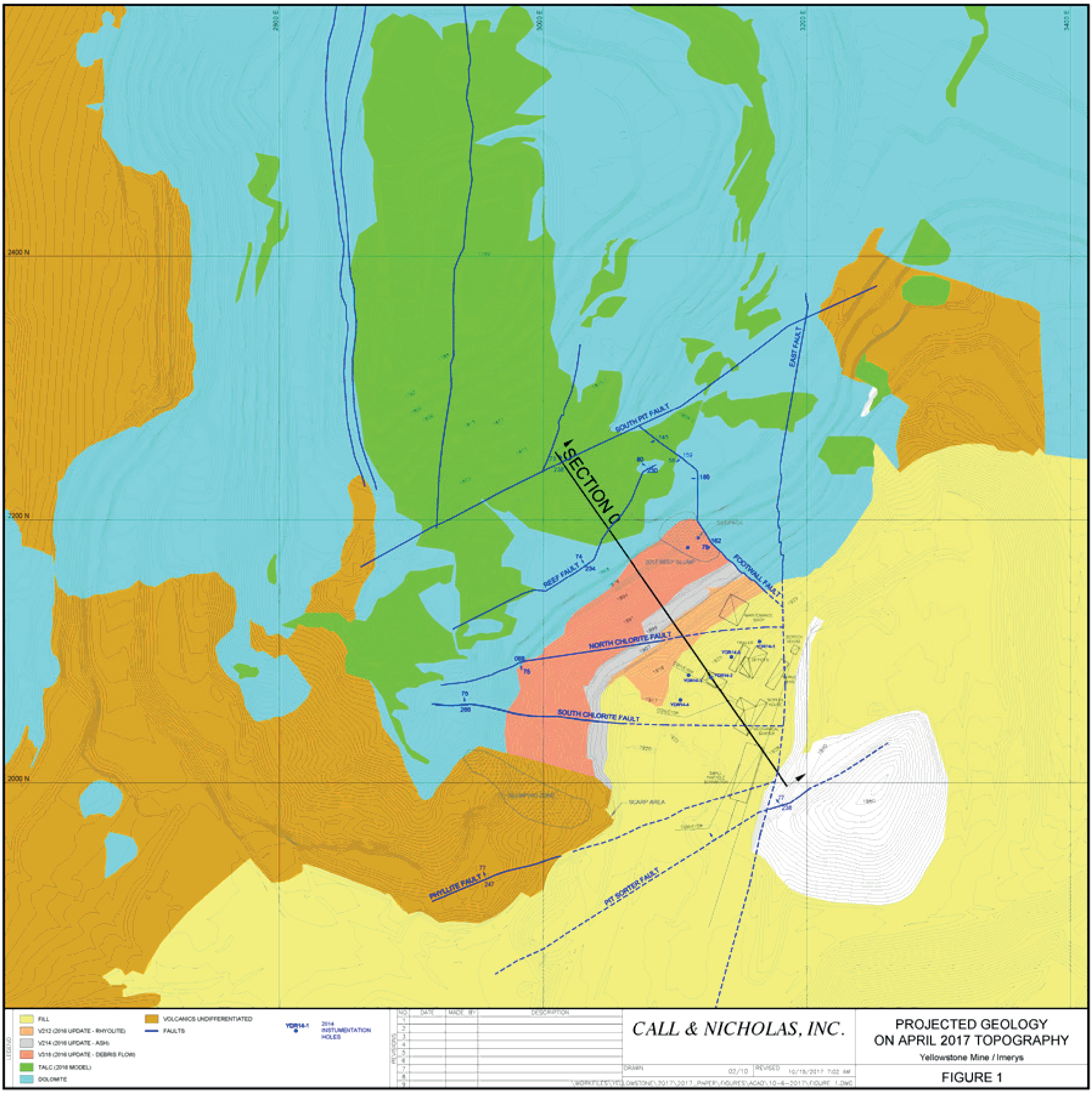


FIGURE 1. Geological Model Projected to April 2017 Topography

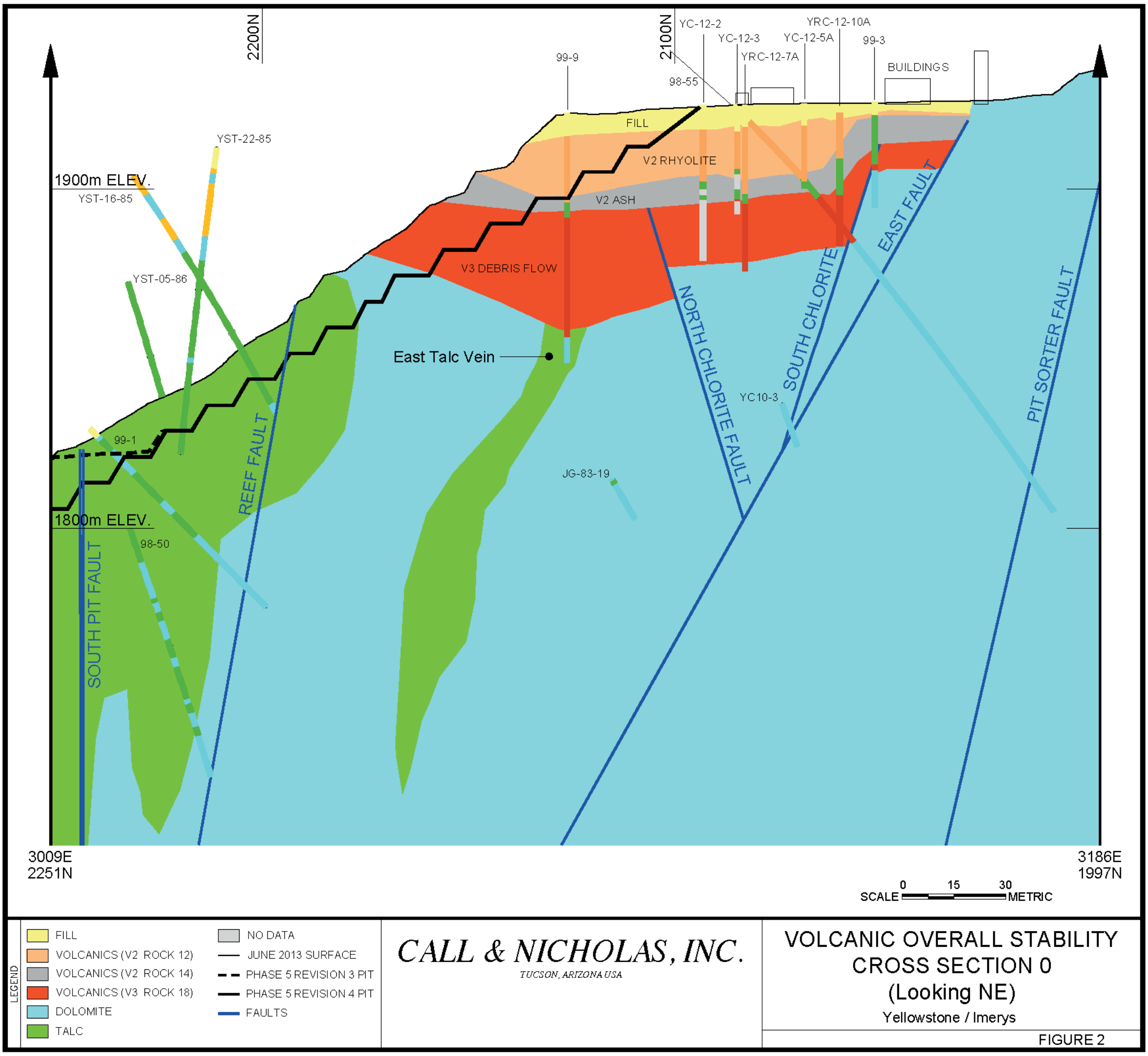


FIGURE 2. Cross Section of the Yellowstone Talc Mine

3. MAJOR STRUCTURE AND ROCK FABRIC

Major structure (discrete faults) are modeled and projected to analyze cross sections. Rock fabric data is used to define anisotropy within the rock mass and used for probabilistic bench-scale analysis. Major faults are mapped with the crest-toe method and rock fabric is mapped using CNI's cell mapping technique (Nicholas & Sims, 2000).

FAULTS

Major structure consists of steeply dipping north-south striking faults and northeast-southwest striking faults. The north-south striking faults generally cross cut the northeast striking faults.

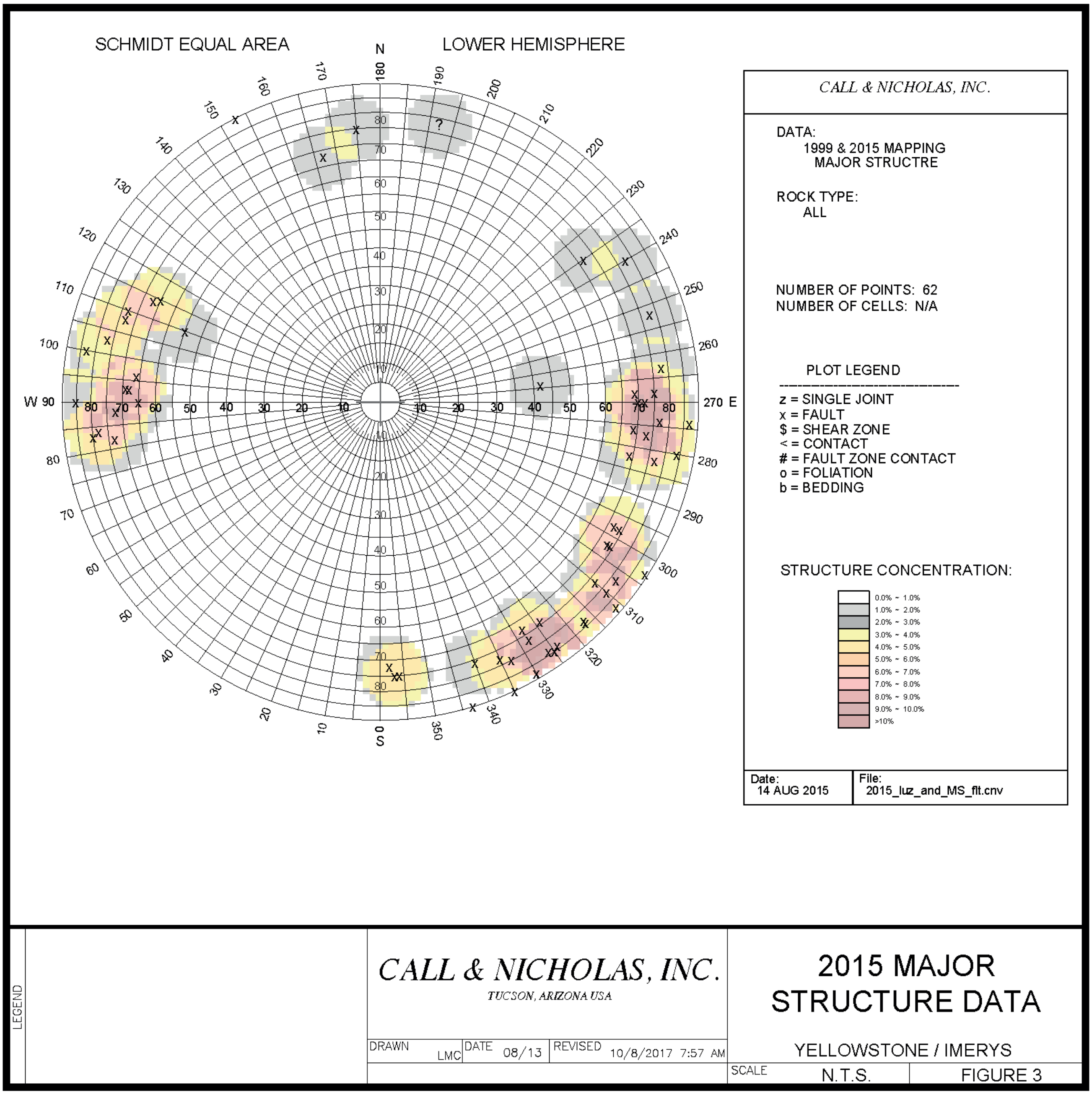


FIGURE 3. Pole Contours of Major Structure

ROCK FABRIC

Joint orientations from cell mapping and oriented core are shown below for dolomitic marble and talc bedrock units.

Talc Rock Fabric

Talc rock fabric is based on 227 cell sets of measurements from cell mapping and oriented core. The data is segregated into 8 geological sets. Orientations are shown in Figure 4, and Table I lists the set statistics, including probability of occurrence, spacing, and length for each geological set.

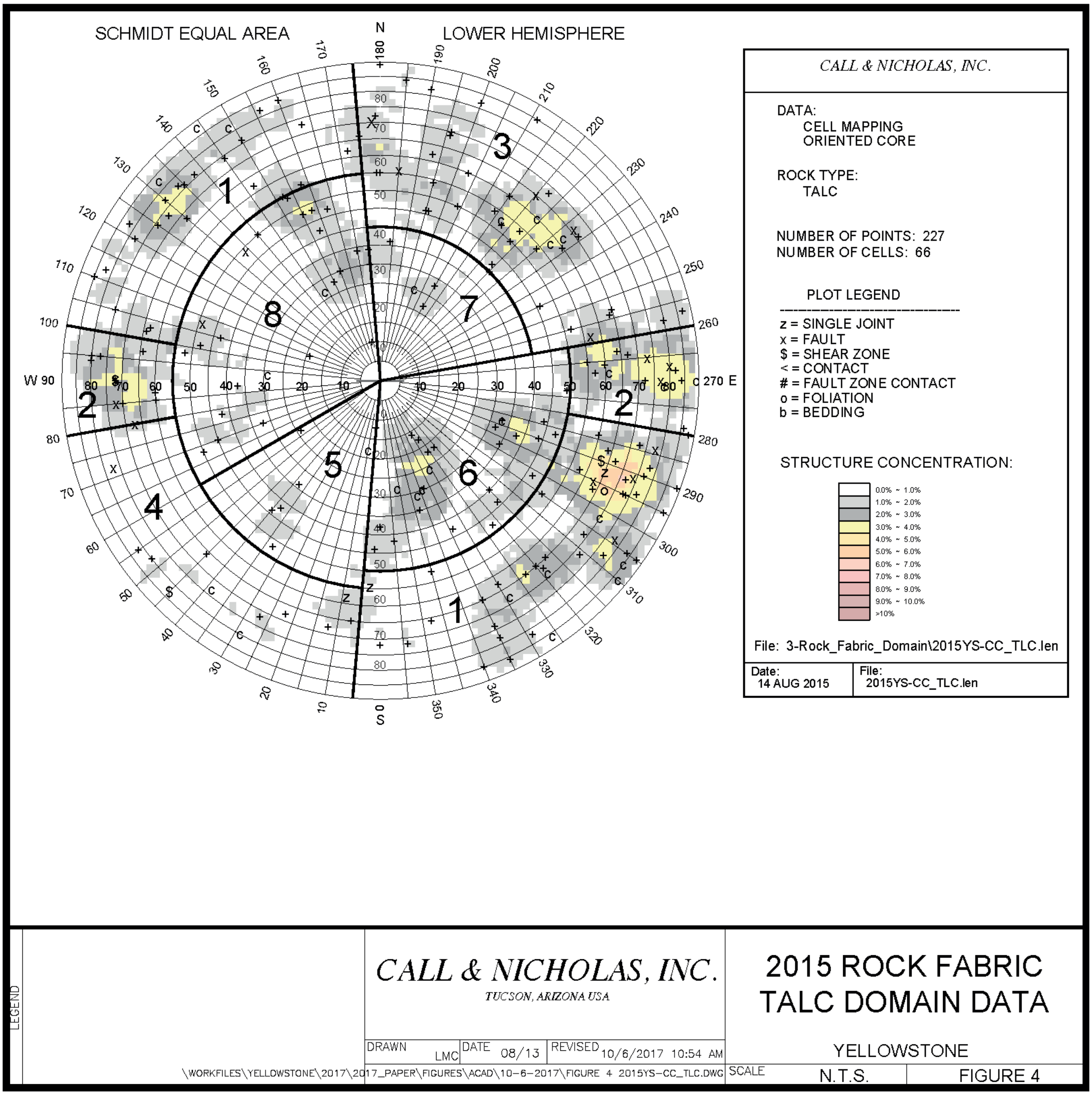


FIGURE 4. Pole Contours of Talc Rock Fabric

TABLE I. Joint Set Statistics of Talc Rock Fabric from Cell Mapping and Oriented Core Data

TABLE I. TALC ROCK FABRIC SET STATISTICS

Set	Probability of Occurrence (%)	DIRECTION	DIP	SPACING	LENGTH	
		Mean (deg)	Mean (deg)	Mean (Mt.)	Mean (Mt.)	MAX (Mt.)
1	77.3	312.1	83.1	0.5	3.2	4.3
2	33.3	269.4	87.6	0.6	4.9	5.6
3	48.5	219.3	64.3	0.6	2.7	4.2
4	19.7	051.8	75.8	0.5	0.8	3.1
5	9.1	036.2	35.7	1.0	3.1	3.6
6	42.4	318.2	35.6	1.0	2.5	3.3
7	7.6	205.8	30.2	1.0	2.1	2.9
8	31.8	128.9	39.7	0.7	1.8	2.8

DOLOMITE ROCK FABRIC

Dolomite rock fabric is based on 334 measurements from cell mapping and oriented core. Figure 5 presents orientations of 8 geological sets and Table II presents the set statistics.

Set 1 represents the main foliation orientation of the dolomite and talc and corresponds to the north-east striking major structure.

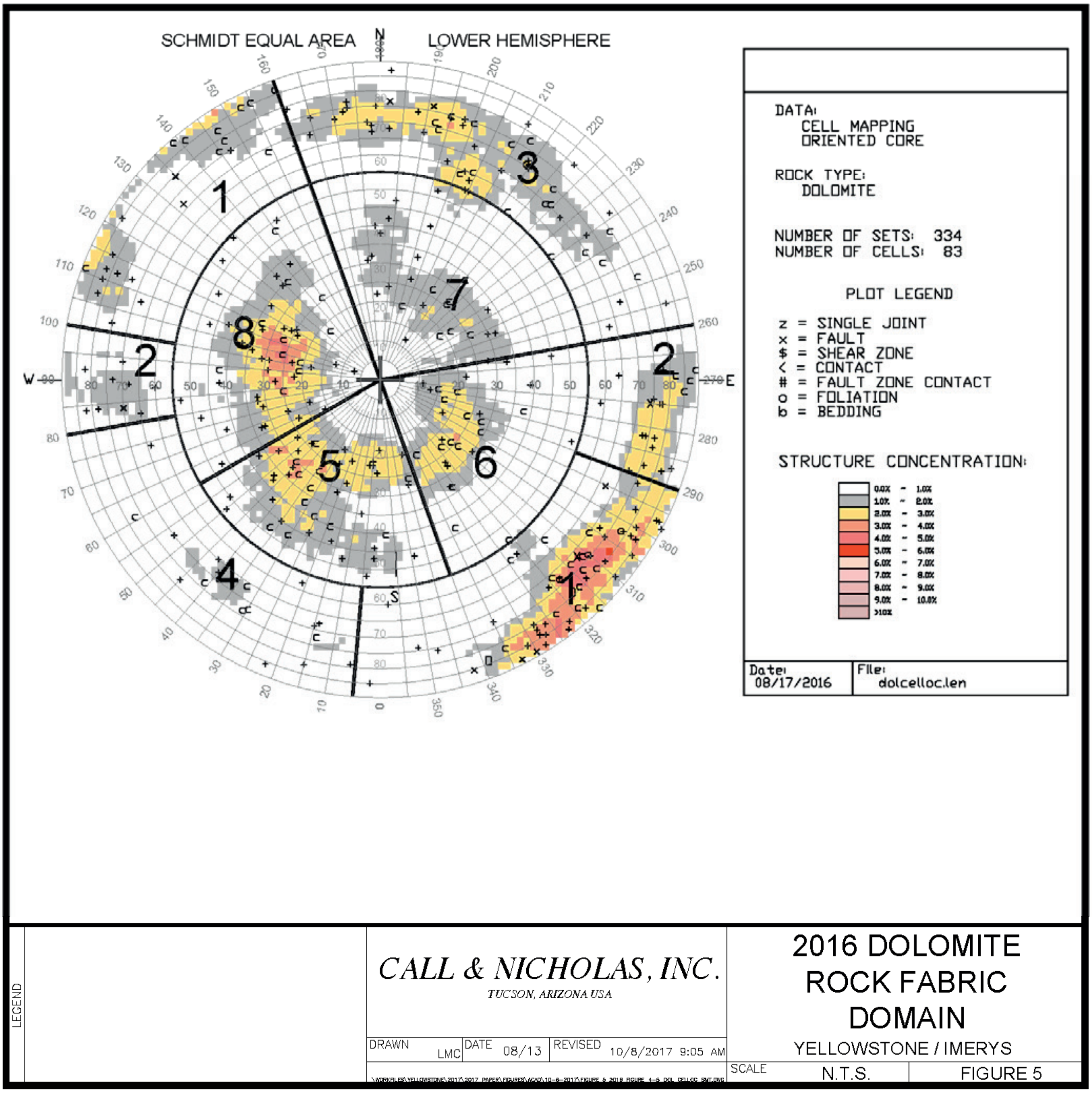


FIGURE 5. Pole Contours of Dolomite Rock Fabric

TABLE II. Joint Set Statistics of Dolomite Rock Fabric from Cell Mapping and Oriented Core Data

TABLE II. DOLOMITE ROCK FABRIC SET STATISTICS

Set	Probability of Occurrence (%)	DIRECTION	DIP	SPACING	LENGTH	
		Mean (deg)	Mean (deg)	Mean (Mt.)	Mean (Mt.)	MAX (Mt.)
1	75.9	314.1	84.6	0.4	3.6	5.4
2	30.1	275.4	86.2	0.5	2.8	4.8
3	54.2	207.2	71.3	0.6	2.3	4.1
4	20.5	032.8	71.8	1.1	2.9	3.6
5	45.8	026.4	32.6	0.8	2.2	3.8
6	31.3	297.0	27.6	0.7	0.9	2.0
7	30.1	209.4	31.3	0.7	1.8	3.3
8	48.2	105.5	31.2	0.7	2.7	3.9

4. HYDROLOGY

The regional water table is below the Phase 5 pit bottom. Piezometers monitor the pore pressures in the mill facility area in the volcanic units. Generally, the piezometers indicate dry conditions; however, perched water appears during the spring melting period near the V3 contact with dolomite adjacent to the Footwall Fault. Surface water is diverted to the south to minimize infiltration to the slope. Snow removal from the mill site area is also a key element of reducing surface water infiltration.

5. SEISMICITY

For overall slope analyses, a ground acceleration of 4%g is used and is based on a historical seismic study which provides probability of exceedance of future ground accelerations. A 4%g value is reasonable based on the expected duration of the Phase 5 mining.

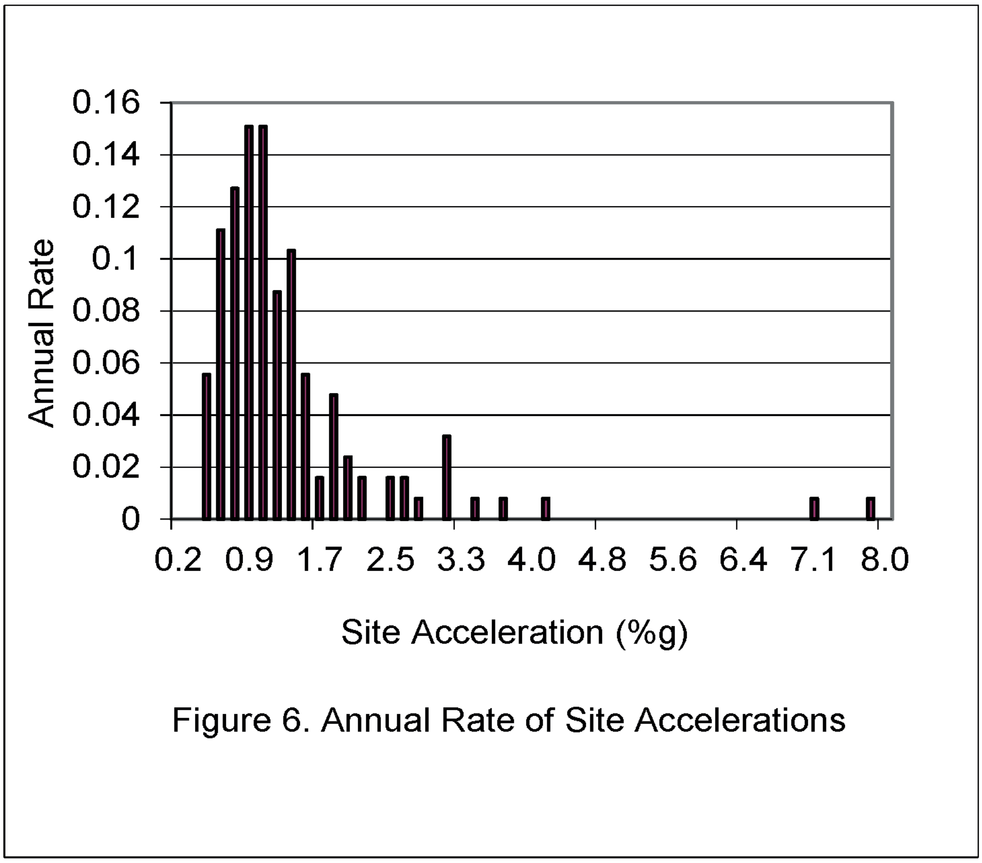


FIGURE 6. Annual Rate of Site Accelerations

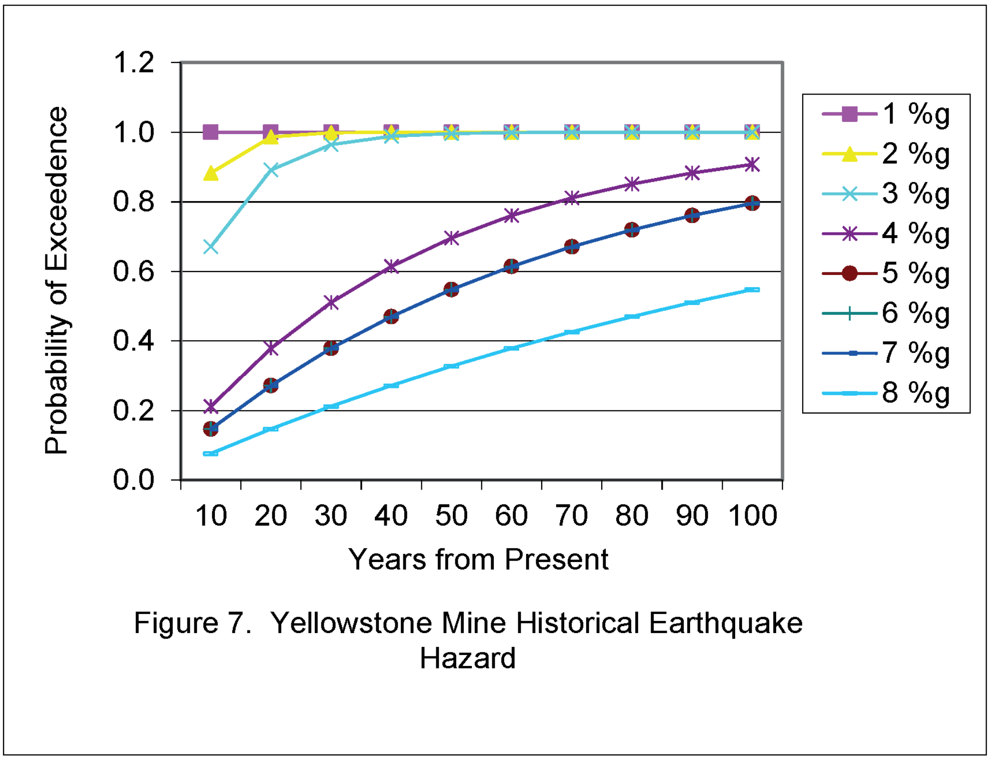


FIGURE 7. Yellowstone Mine Historical Earthquake Hazard

6. MATERIAL PROPERTIES

Rock mass shear strengths for V2 ash and V3 debris flow are derived from direct shear testing due to their soil-like characteristics. Rock mass strengths for bedrock units of talc, dolomite, and V2 rhyolite are estimated using laboratory testing (fracture shear testing and intact testing) in combination with RQD measurements using CNI's rock mass criterion (Call et al. 2000) and (Call & Nicholas Inc. 2009).

Minus one standard deviation strength is determined by the variability of direct shear testing results for soil units. For bedrock units, the minus one standard deviation strength is estimated by assuming the fracture shear strength is minus two standard deviations from the rockmass mean.

TABLE III. Mean and Minus One Standard Deviation Rock Mass Strengths

TABLE III. MEAN AND MINUS 1 STANDARD DEVIATION ROCK MASS STRENGTHS

Rock Type	Density	Intact		Direct Shear		RQD	Rockmass Mean		Rockmass -1 Standard Dev.	
	(gm/cm^3)	φs	Cs (KPa)	φf	Cf (KPa)	%	φm	Cm (KPa)	φm	Cm (KPa)
Fill	2.1	-	-	-	-	-	36.0	0.0	36.0	0.0
V2 Rhyolite	1.5	38.5	4455.4	35.6	59.6	0.0	36.0	141.3	35.8	100.3
V2 -Ash	1.6	-	-	35.0	33.3	-	35.0	33.3	33.7	28.1
V3 -Debris Flow	1.9	-	-	17.3	59.6	-	17.3	59.6	14.9	50.3
Dolomite	2.9	49.1	2883.7	24.8	49.2	12.0	30.1	710.2	27.5	379.7
Talc	2.8	29.0	794.5	12.2	20.8	8.0	15.2	180.6	13.7	100.7

Anisotropy is incorporated into the rock mass for talc and dolomite bedrock based on rock fabric mapping. For talc and dolomite, three anisotropic orientations are defined:

A steep back plane set representing foliation (rock fabric set 1), assigned a 100% talc fracture strength.

A plane shear set (rock fabric set 6), assigned a 2.5% intact strength and 97.5% fracture strength by rock type.

A toe set dipping back into the wall (rock fabric set 8), assigned a 100% fracture strength by rock type.

TABLE IV. Back Analyzed Rock Mass Strengths with Anisotropy

Talc							
Geological Set Number	Range From (deg)	Range To (deg)	Intact %	Rock Mass Strength		Anistropic Strength	
				Phi	Cohesion (Kpa)	Phi	Cohesion (Kpa)
1 (Back Plane)	60	90	0	-	-	12.2	20.8
Rock Mass	45	59	-	15.2	180.6	-	-
6 (Plane Shear)	26	44	2.5	-	-	12.7	157.2
Rock Mass	-22	25	-	15.2	180.6	-	-
8 (Toe Set)	-23	-45	0	-	-	12.2	20.8
Dolomite							
Geological Set Number	Range From (deg)	Range To (deg)	Intact %	Rock Mass Strength		Anistropic Strength	
				Phi	Cohesion (Kpa)	Phi	Cohesion (Kpa)
1 (Back Plane)	60	90	0	-	-	12.2	20.8
Rock Mass	45	59	-	30.1	710.2	-	-
6 (Plane Shear)	26	44	2.5	-	-	25.4	545.1
Rock Mass	-22	25	-	30.1	710.2	-	-
8 (Toe Set)	-23	-45	0	-	-	24.8	49.2

7. BENCH-SCALE STABILITY ANALYSES

Bench-scale analyses define the bench layout and interramp slope angle (ISA) for adequate catchment. Mine planners use the ISA recommendations from the bench-scale analyses to generate preliminary mine plans.

BENCH-SCALE CRITERIA AND ANALYSIS

Catch bench criteria at Yellowstone is based on the Modified Ritchie Criterion as a guide for designing catch bench widths (CBWs) (Ritchie, 1963).

MODIFIED RITCHIE CRITERION FOR CBW FOR YELLOWSTONE

For single benches (7.62 m high):
*CBW (m) = 0.2*bench height + 3.05m = 4.57m*
(Reliability 60% to 80%)

Talc slopes are excavated without blasting, while dolomite slopes use trim-row and pre-split blasting methods.

The result from the bench-scale analysis is a cumulative distribution of expected bench face angles (BFAs). Measured BFAs from the field are used to calibrate the analysis.

Talc BFA Distributions and Interramp Design

BFA distributions for talc are shown in Figure 8. Figure 9 is a cross section of the ISA layout.

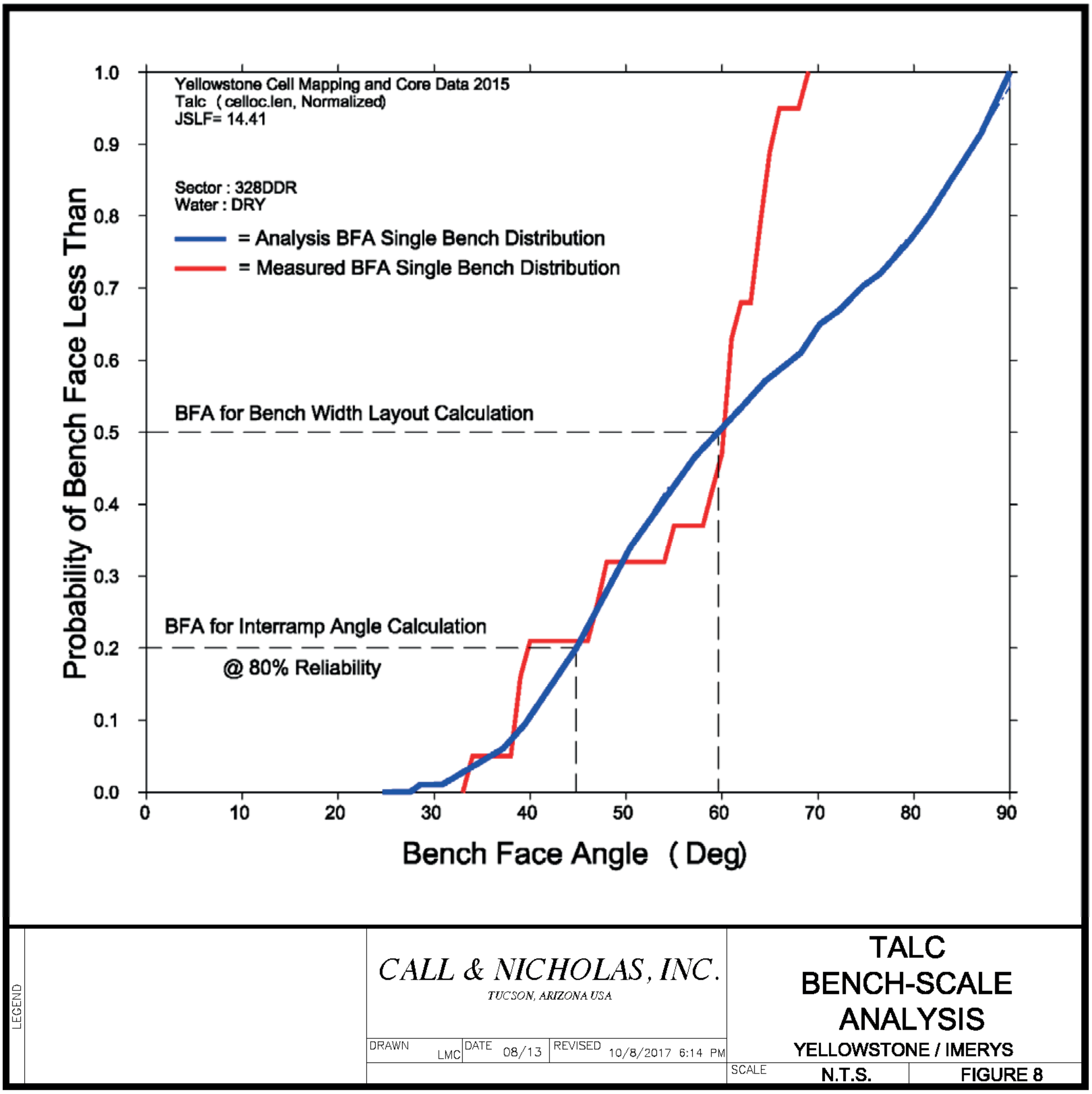


FIGURE 8. Talc BFA Distributions for Measured Data (Red) and Analyzed BFA (Blue)

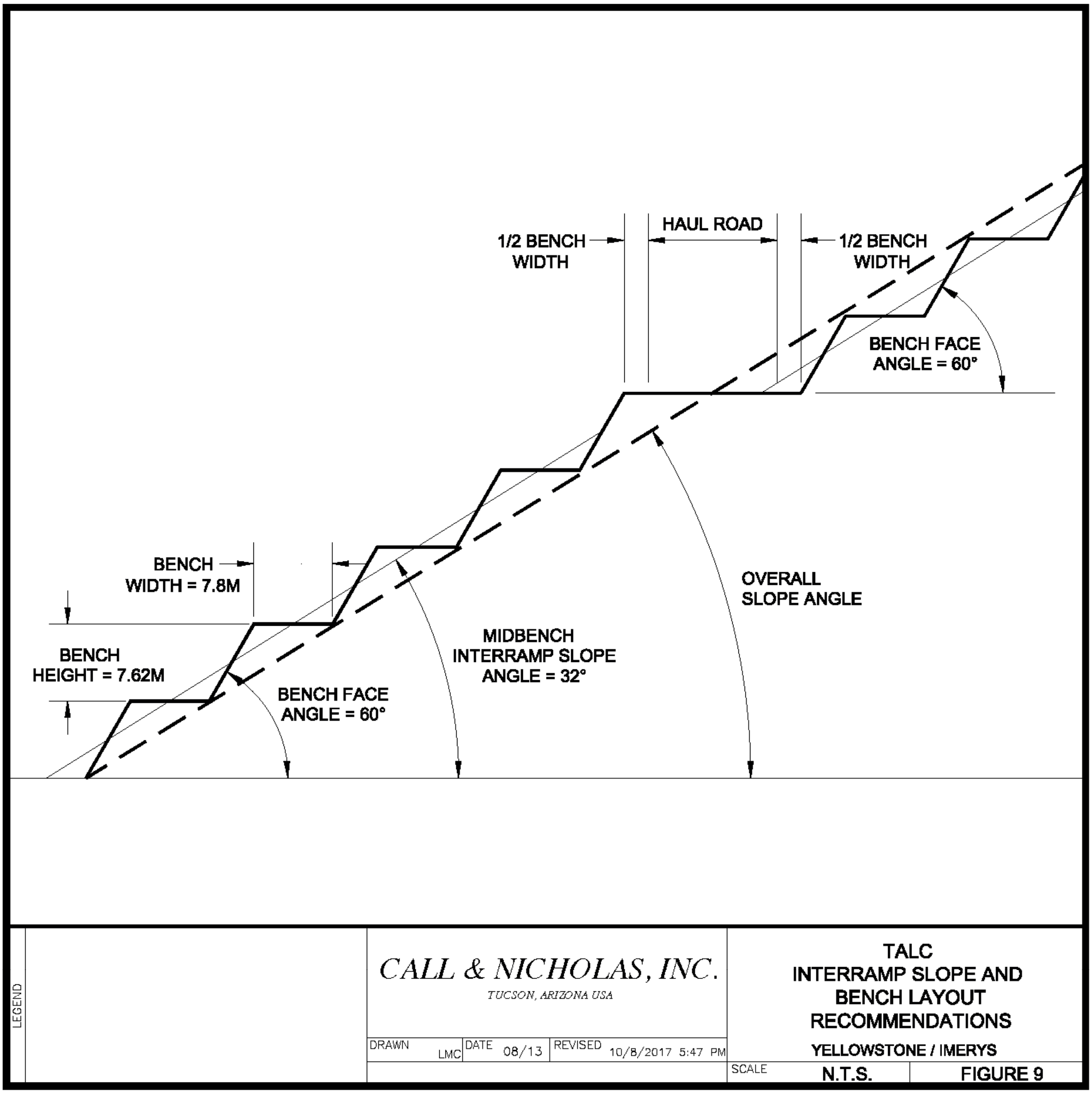


FIGURE 9. Talc 32-Degree Interramp Slope Angle Design Layout

Dolomite BFA Distributions and Interramp Design

BFA distributions for dolomite are shown in Figure 10. Figure 11 is the dolomite ISA design layout for talc in cross section.

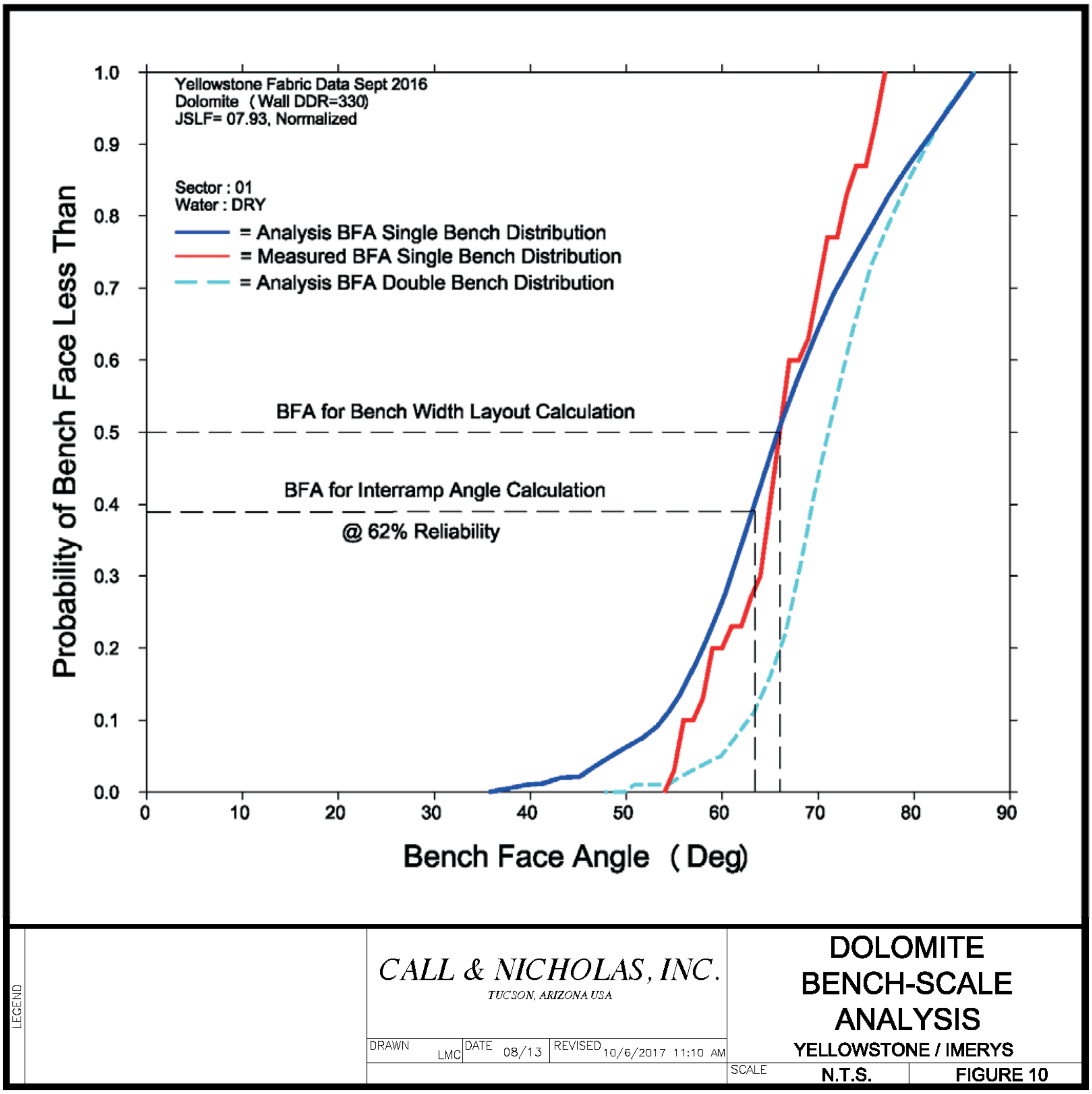


FIGURE 10. Dolomite BFA Distributions for Measured Data (Red) and Analyzed BFA (Blue)

The measured curve in Figure 10 shows the dolomite measured BFAs are steeper than the analysis BFAs due to improved excavation practices from pre-splitting.

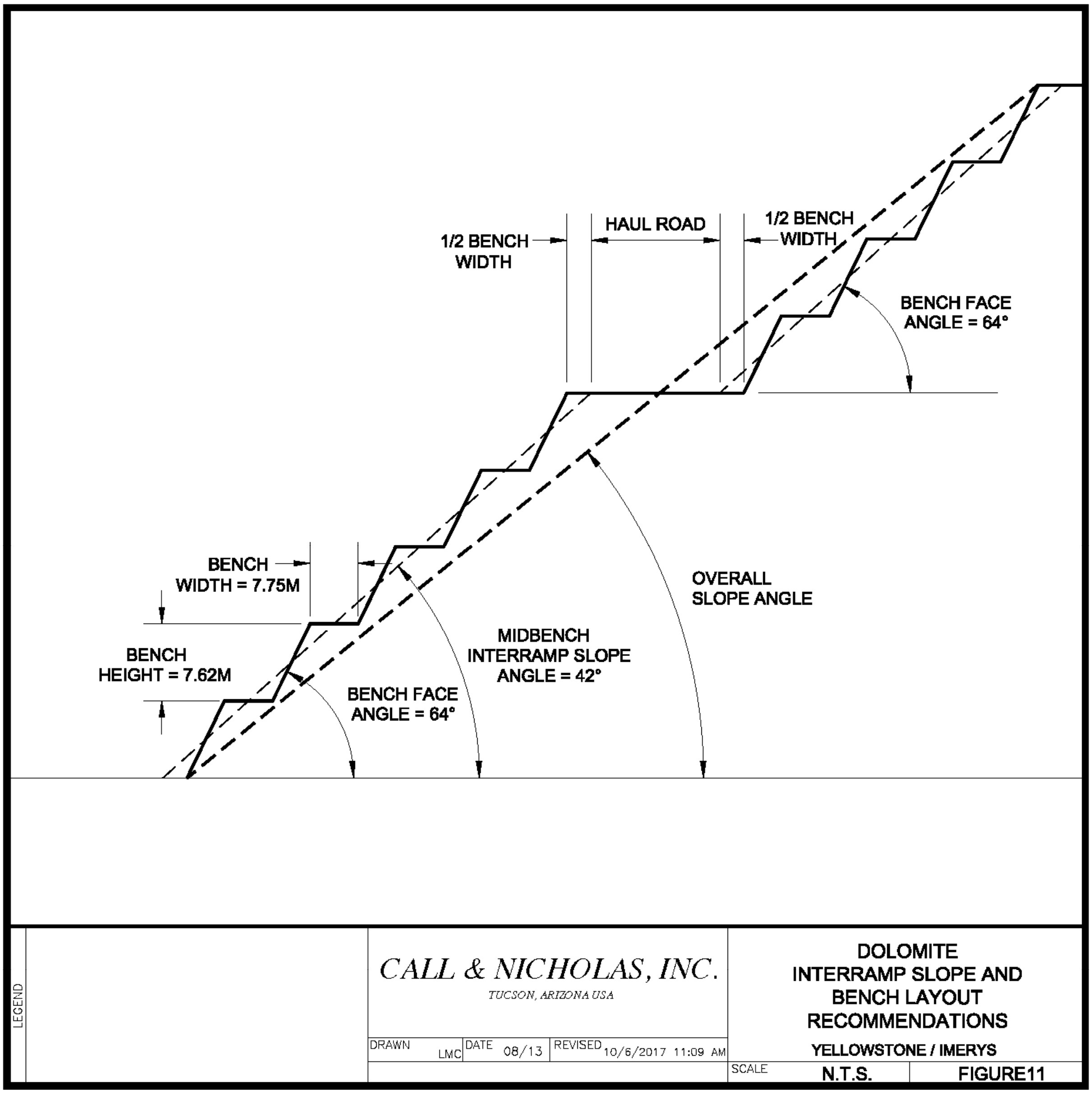


FIGURE 11. Dolomite 42-Degree Interramp Slope Angle Design Layout

OPPORTUNITIES OUTSIDE PHASE 5 MILL SLOPES

Dolomite is considered for double benching outside the mill slopes in future phases. The predicted BFA curve from analysis is shown in blue in Figure 10. Double benching in dolomite can increase the interramp angle by 3-degrees and increase reliability of the bench design (Ryan and Pryor, 2000). Double benching significantly reduces stripping costs and is considered for future mining phases (dashed light blue line on Figure 10).

8. OVERALL SLOPE STABILITY ANALYSES

Phase 5 mine plans were developed based on the ISA generated from the bench-scale analyses for talc and dolomite. Several design options were analyzed for overall stability. Limit Equilibrium analyses and FLAC analysis were used to define a suitable stable overall slope angle (OSA) design.

Limit Equilibrium Overall Slope Analyses

A back analysis of the 2004 failure topography was performed to calibrate input parameters. The talc slope was steepened to 40-degrees causing unstable slope conditions at the time of failure. Figure 12 is a photo of the 2004 talc failure taken in 2015. The mill facility is shown at the crest above the failure. Rock fall berms are shown at the failure base and the interramp angle below the failure is stable at a 32 degree ISA.

FIGURE 12. 2004 Talc Nose Failure (Looking Southeast)

The critical failure surface is non-circular following the anisotropy applied to the model.

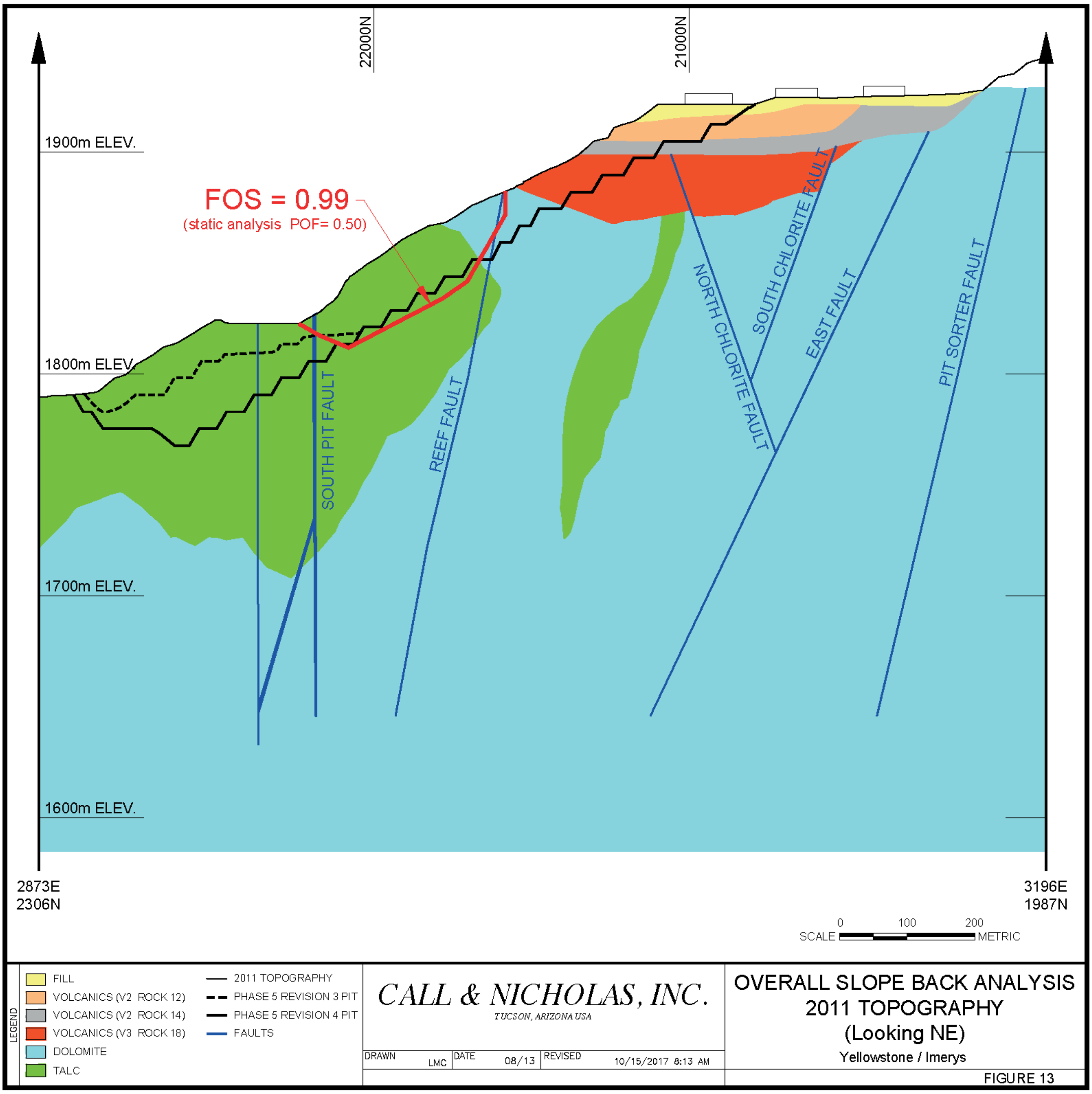


FIGURE 13. Limit Equilibrium Back Analysis

Phase 5 forward analyses require a 32-degree ISA slope and a mid-slope ramp in the talc to maintain OSA stability. Alternative mine plans without a mid-slope ramp did not meet the OSA stability criteria. The Phase 5 Revision 3 mine plan shown in Figure 13 meets the criteria.

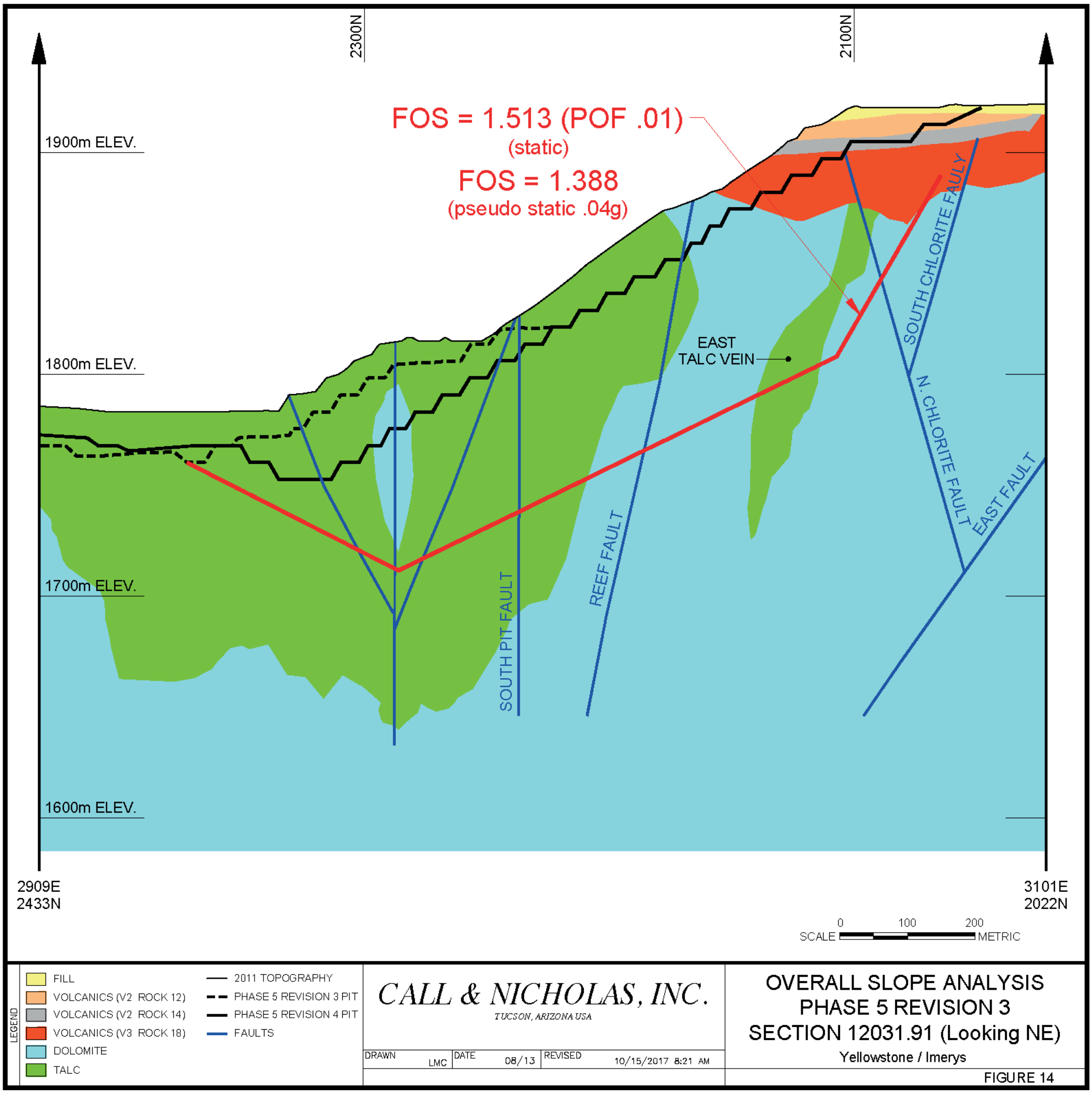


FIGURE 14. Limit Equilibrium Analysis for Phase 5 Revision 3 Mine Plan (dashed black topography)

VOLCANIC SLOPE STABILITY

Limit equilibrium analyses in the upper slope volcanic units were used to determine a stable overall slope angle (34 degrees) that meets the overall slope angle criteria.

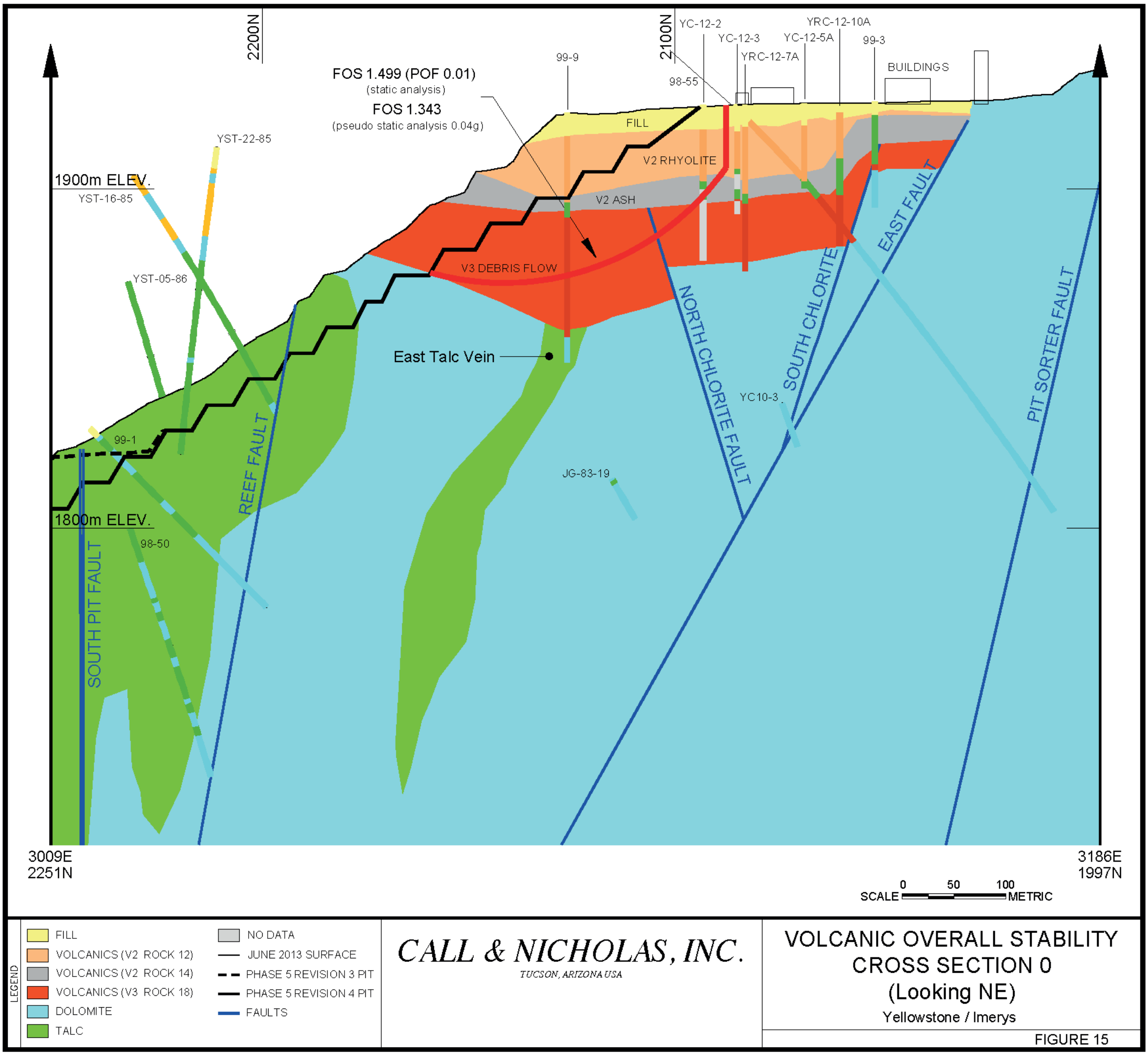


FIGURE 15. Volcanic Overall Slope Stability

FLAC Overall Slope Analyses

FLAC analysis is necessary due to contrasting material strengths between dolomite and talc. Dolomite being a brittle, high strength, elastic material compared to the weaker talc unit which comprises the lower portions of the overall slope. A back analysis was performed to calibrate strengths followed by predictive analyses on the Phase 5 pit design.

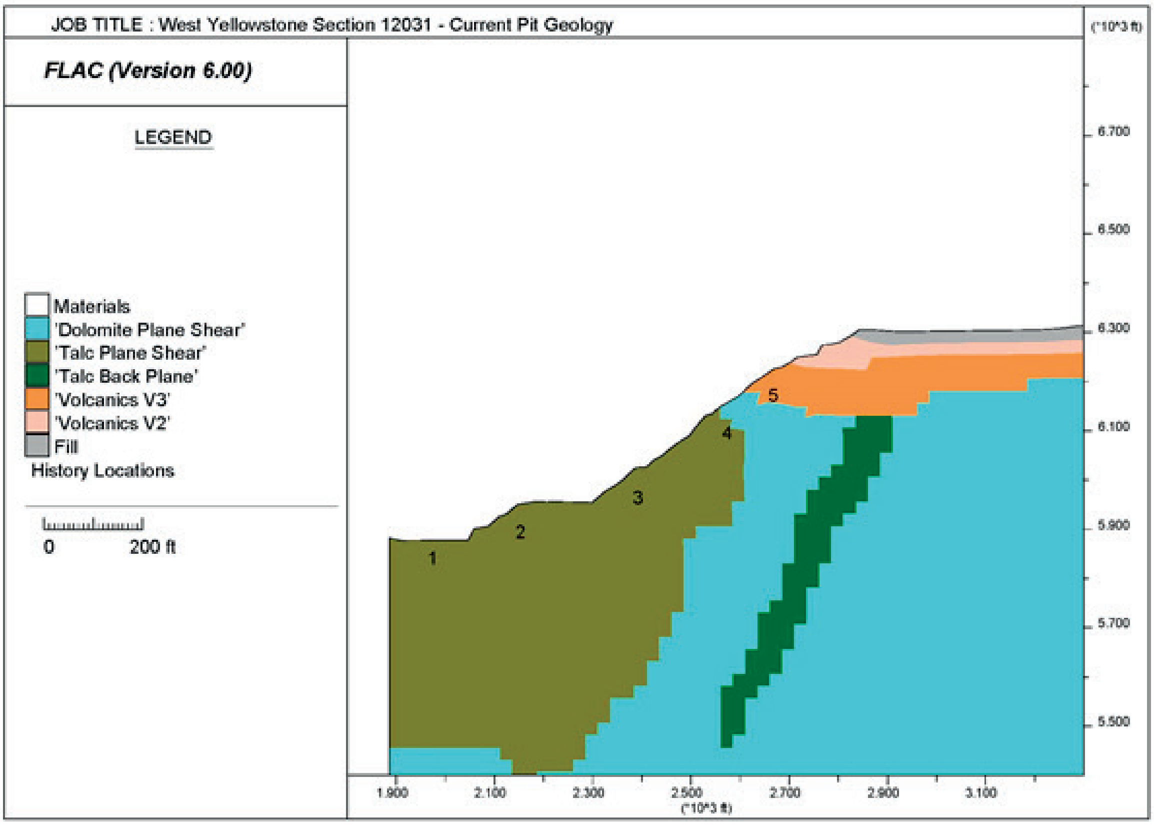


FIGURE 16. FLAC Back Analysis Geology Model with History Points

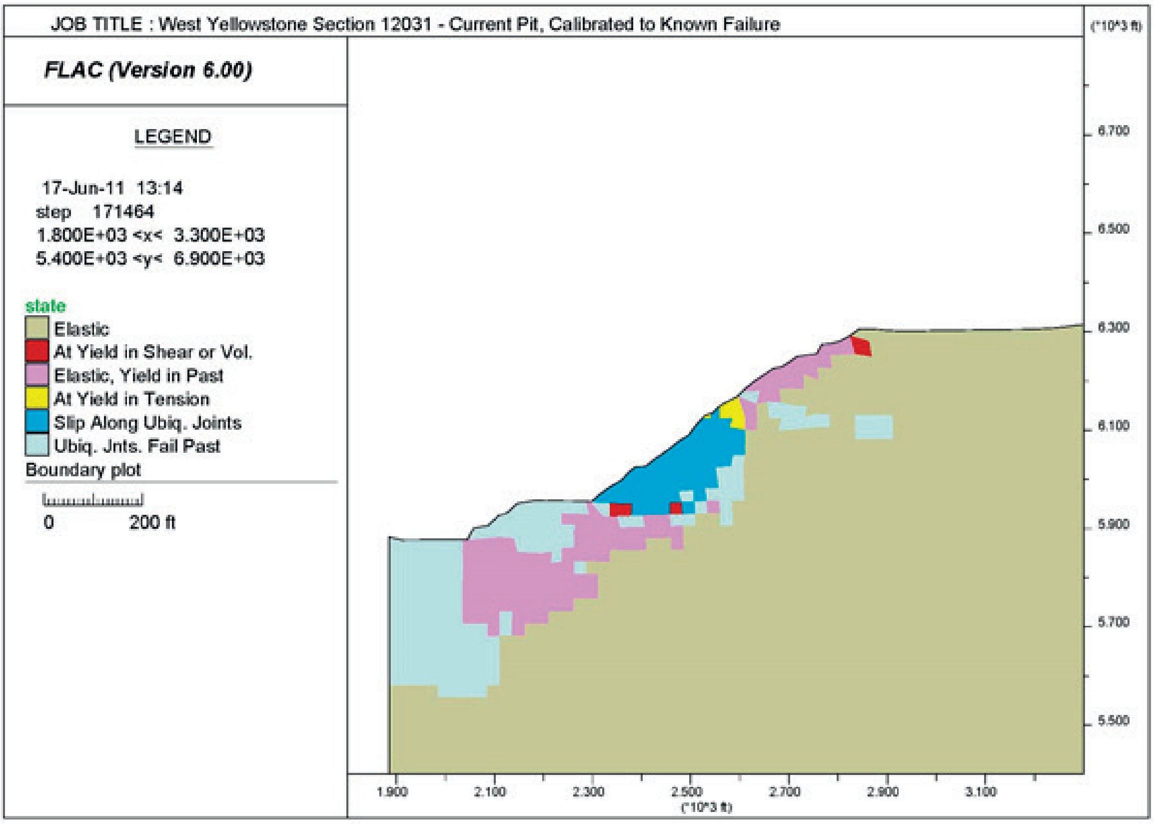


FIGURE 17. FLAC Back Analysis Plasticity State

Strain in the back analysis is limited to talc and along ubiquitous joints. Horizontal displacements are shown in Figure 17 and correlate with prism displacement data.

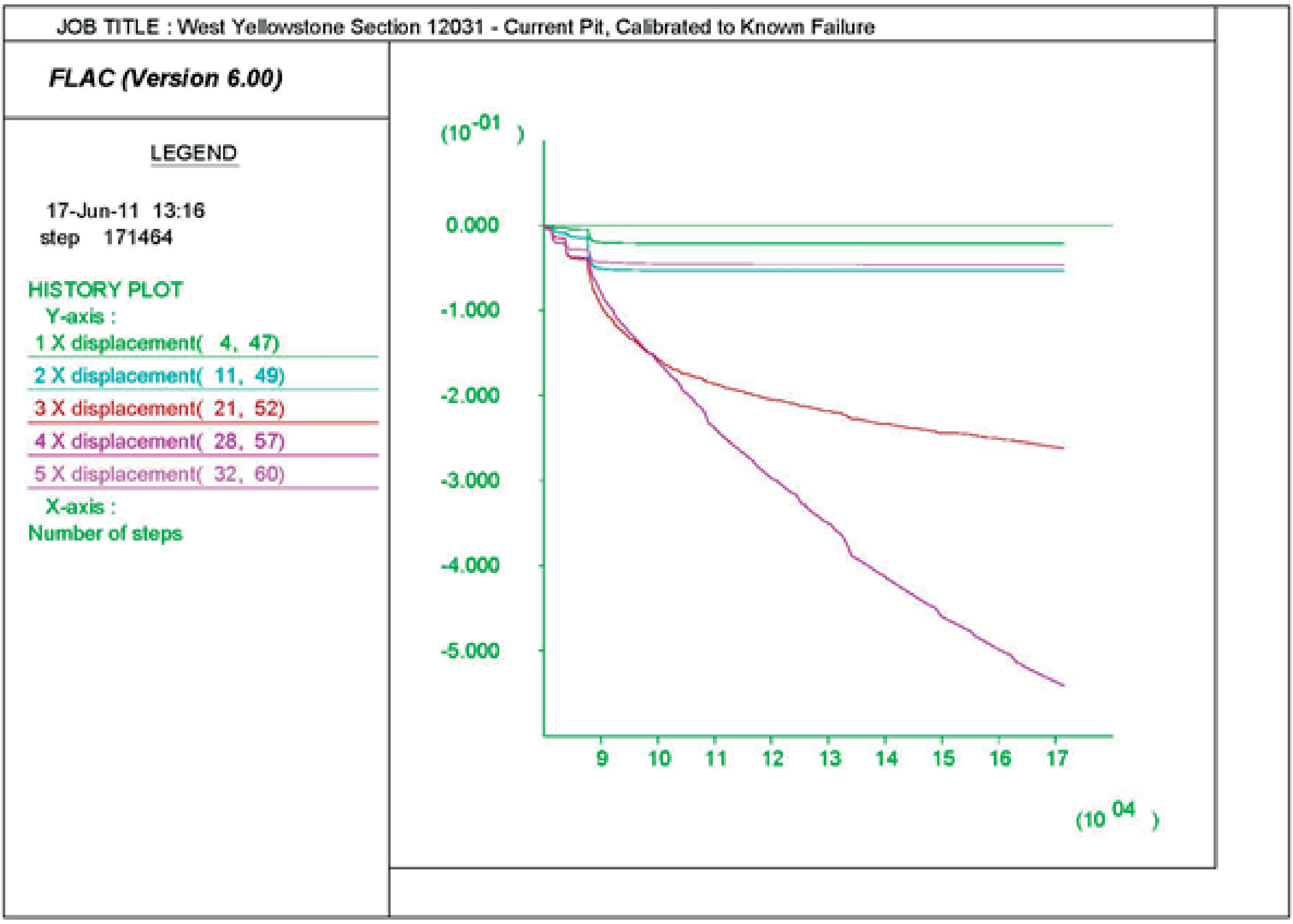


FIGURE 18. FLAC Back Analysis Horizontal Displacement

A predictive analysis on a Phase 5 pit indicates the mine plan is stable with ramps in talc at the mid-slope.

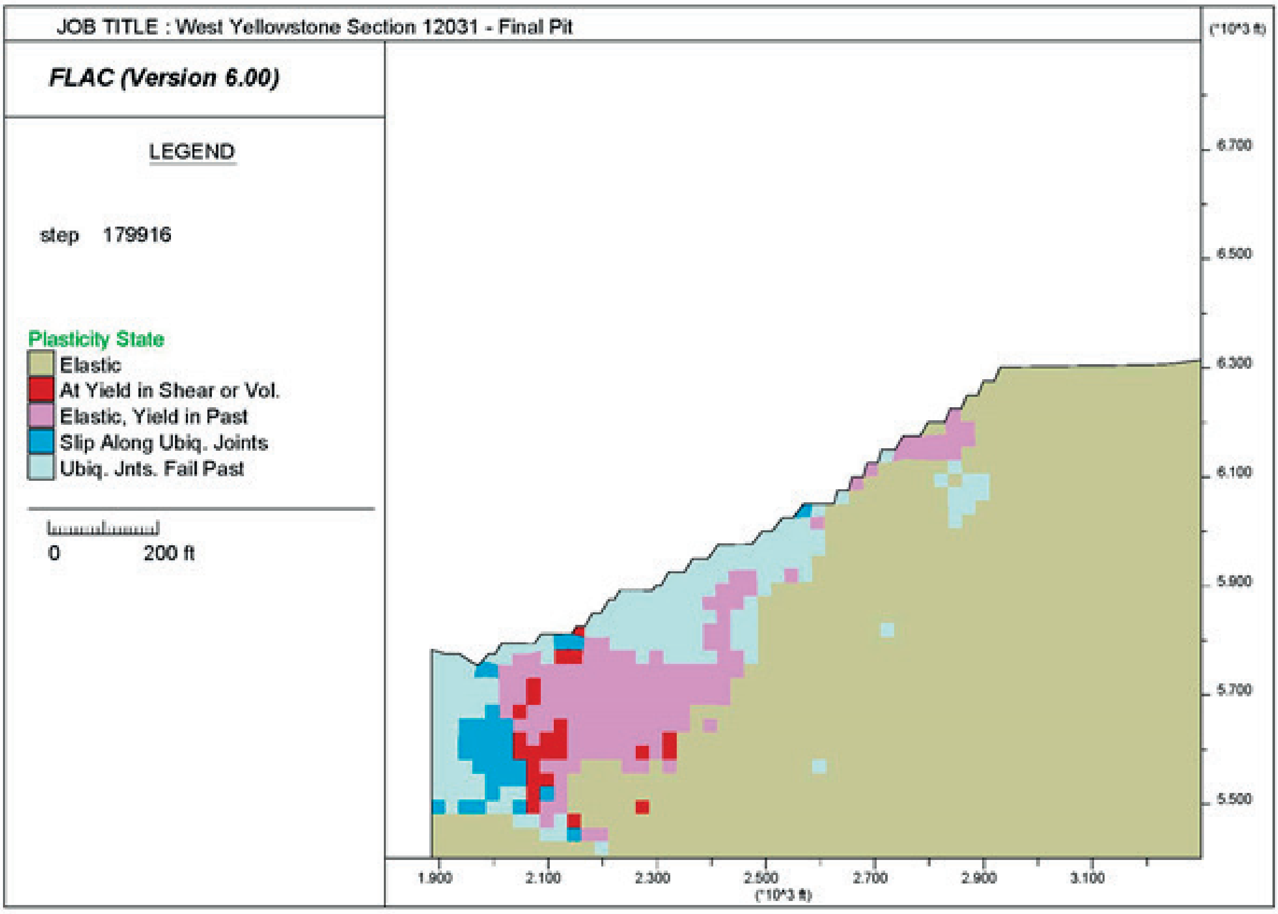


FIGURE 19. FLAC Predictive Analysis Plasticity State

SLOPE DESIGN SUMMARY

The design targets are: 34-degree overall slope angle (OSA) for volcanic slopes; 32-degree ISA in talc, and 42-degree ISA in dolomite. Additionally, a mid-slope ramp in talc slopes are necessary for OSA stability. All overall slope angles achieve a FOS = 1.3 (static) with a POF of 10% or less. Pseudo-static analysis must be FOS = 1.2 or higher.

9. SLOPE STABILITY AND DESIGN VERIFICATION

Verification of the design is based on monitoring data, excavation practices, and measurements of the achieved slope angles.

MONITORING DATA

Slope RADAR, GPS monuments, and prisms monitor slope surface movement. Inclinometers and TDR installations monitor the subsurface in the volcanic units. Vibrating wire piezometers (VWP's) monitor pore pressures in the volcanic soil units in the upper slope and dolomite. Blast vibrations and regional seismic activity data is monitored.

Surface Slope Radar, GPS and Prisms Monitoring

Slope RADAR, GPS monuments, and prism data show the slope surface is stable. Figure 19 is a RADAR survey of the mill slope area in August 2017.

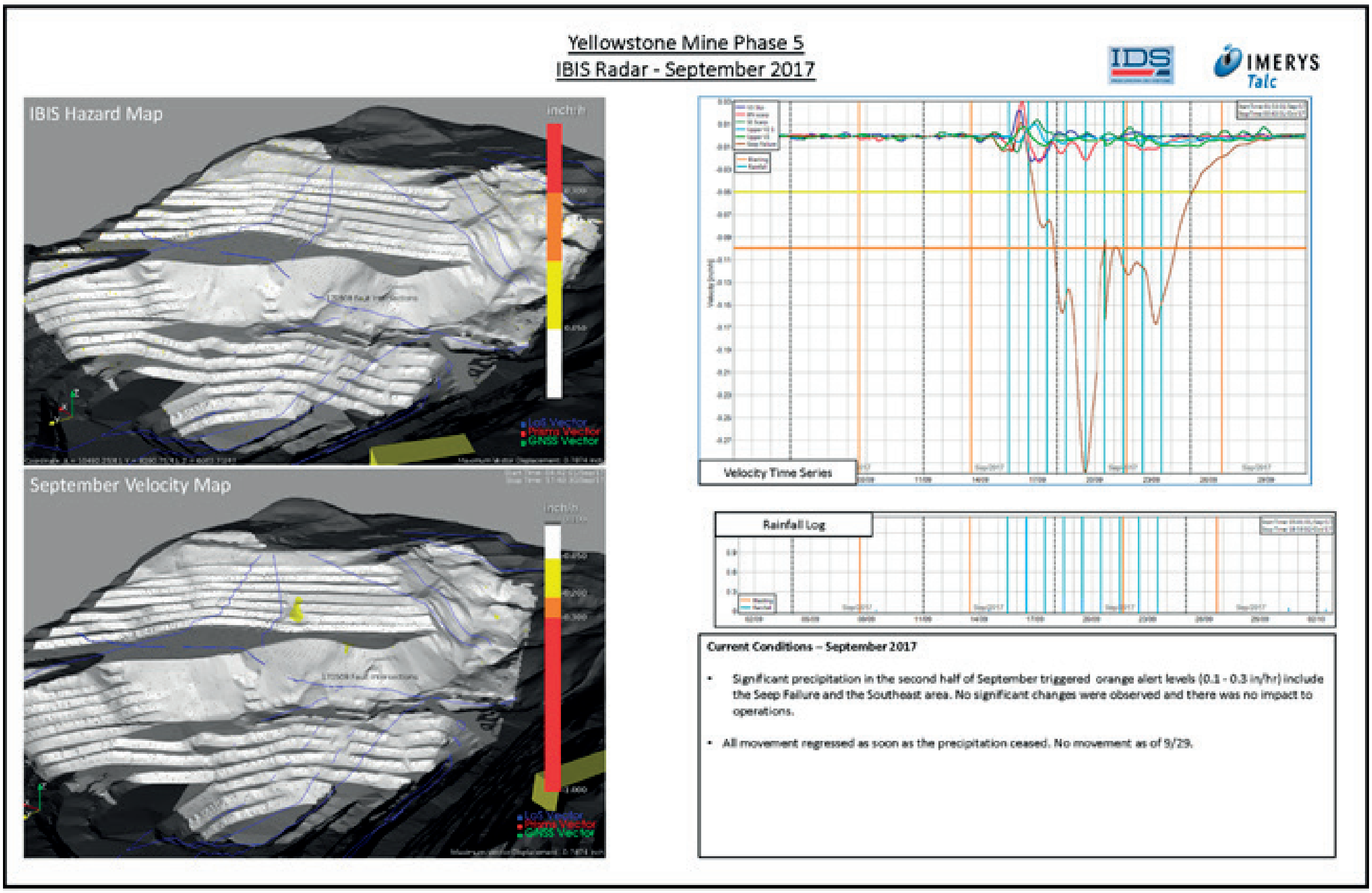


FIGURE 20. Phase 5 Slope RADAR (August 2017)

GPS displacement data for 2014 to July 2017 is shown in Figure 20.

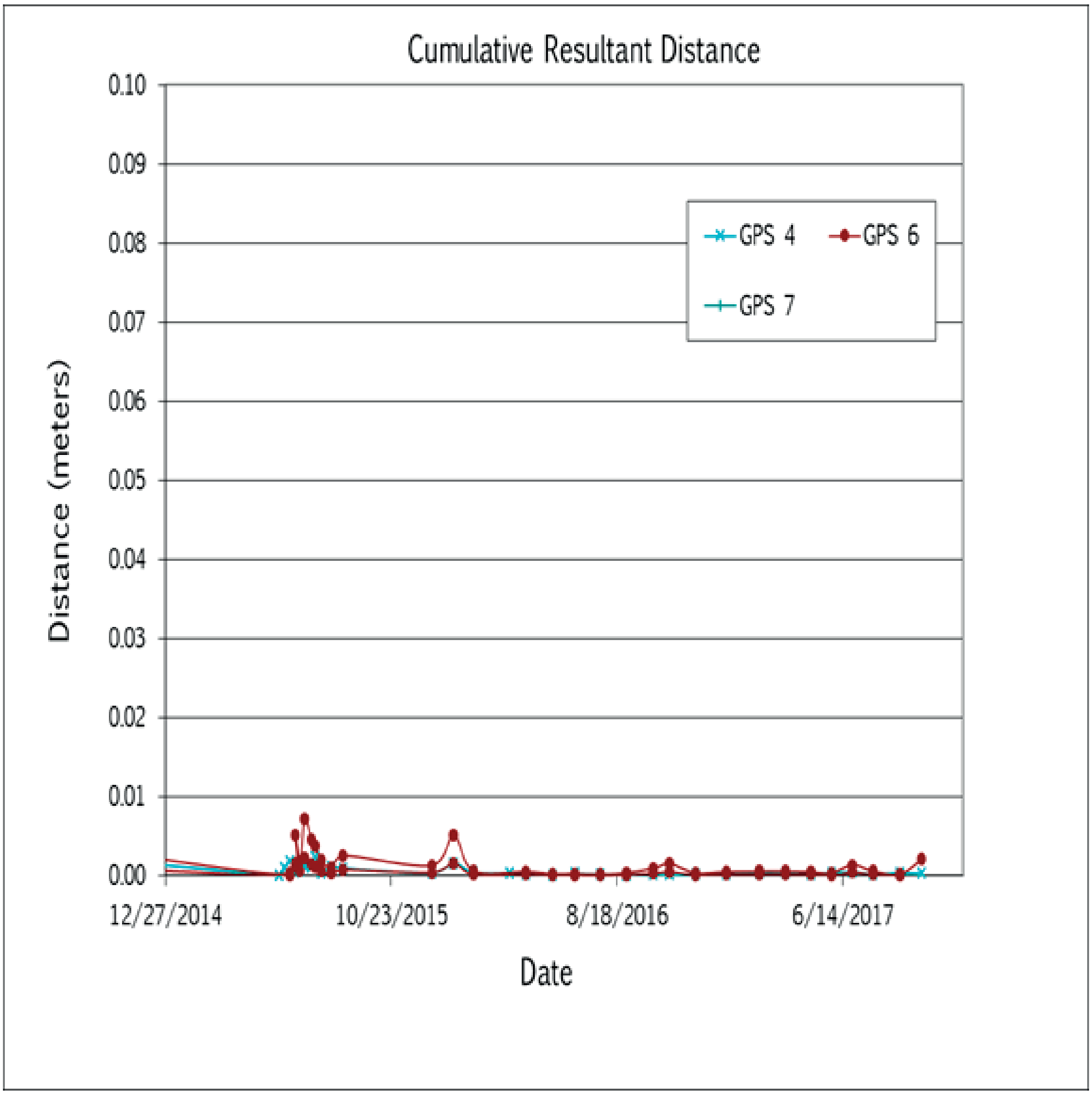


FIGURE 21. Phase 5 GPS Displacement Data

Sub-Surface Inclinometer, TDR, and Piezometer Monitoring

Subsurface monitoring from inclinometer data indicates movement in the sub-surface is well within tolerances for the mill site. Inclinometers closer to the slope crest have less than 1 centimeter of displacement between 2015 and August 2017. This is considered a normal tensional response to mining. Inclinometer and TDR data from 14-2A is provided in Figure 21

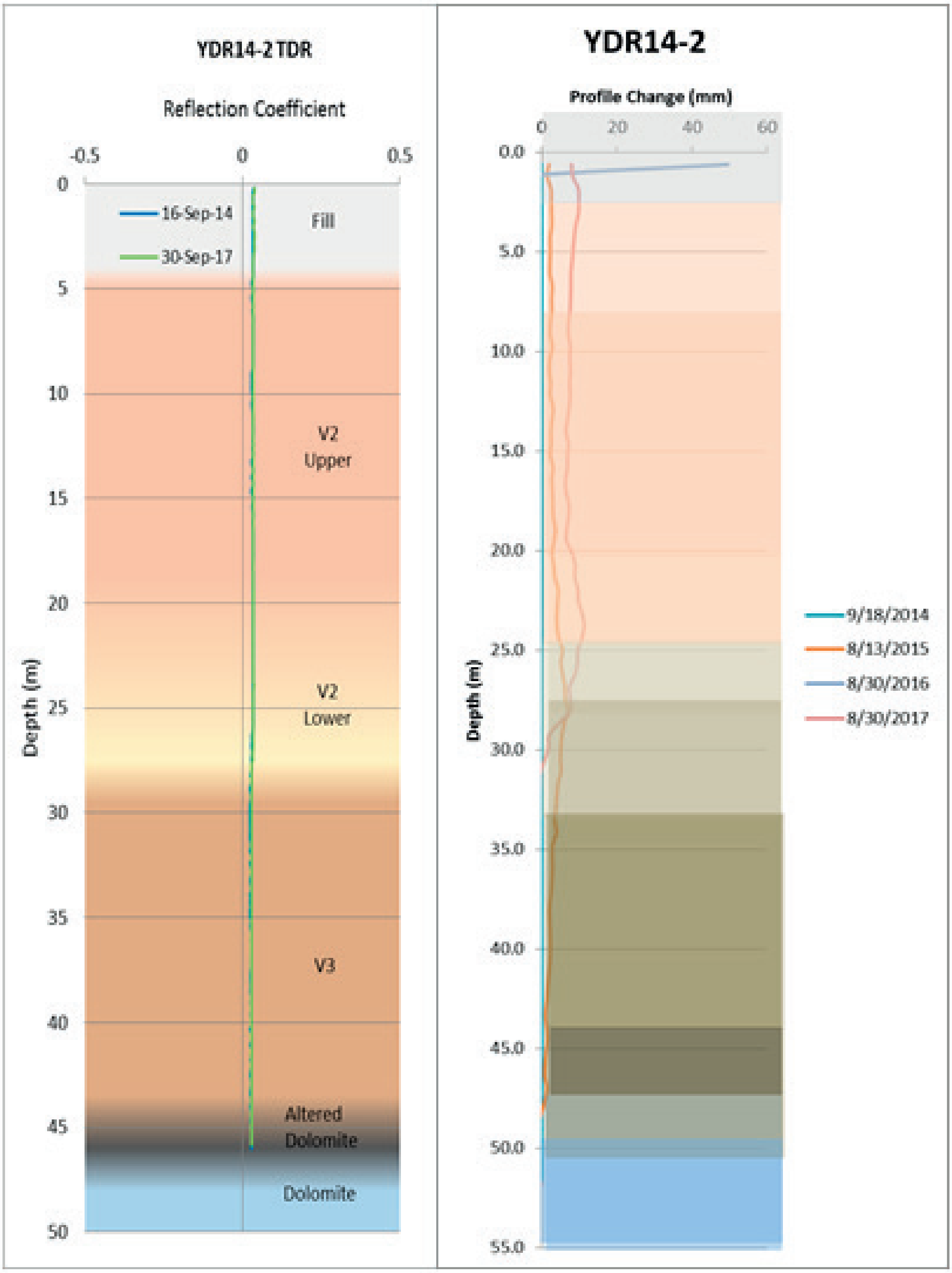


FIGURE 22. Subsurface TDR and Inclinometer Monitoring

All piezometers show dry conditions except YDR14-3. This piezometer is located on the edge of the trough of V3 near the dolomite contact. The piezometer is showing a downward trend in pore pressure since Phase 5 mining began. Additional piezometers are planned to investigate the V3 trough area. Piezometer YDR14-5 shows elevated pressures due to water infiltrating the inclinometer casing. The casing was pumped in June 2017 and the pore pressures dropped immediately.

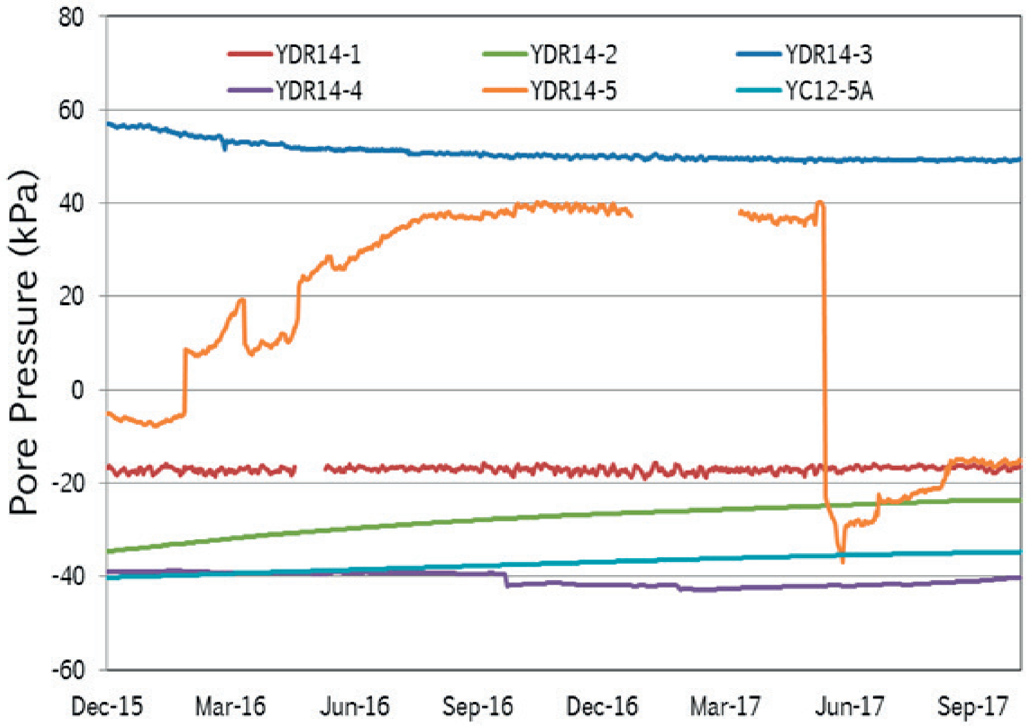


FIGURE 23. Piezometer Monitoring

Seismic and Blast Monitoring

Seismic monitoring is updated with the USGS database. Blast monitoring records particle velocities and frequencies.

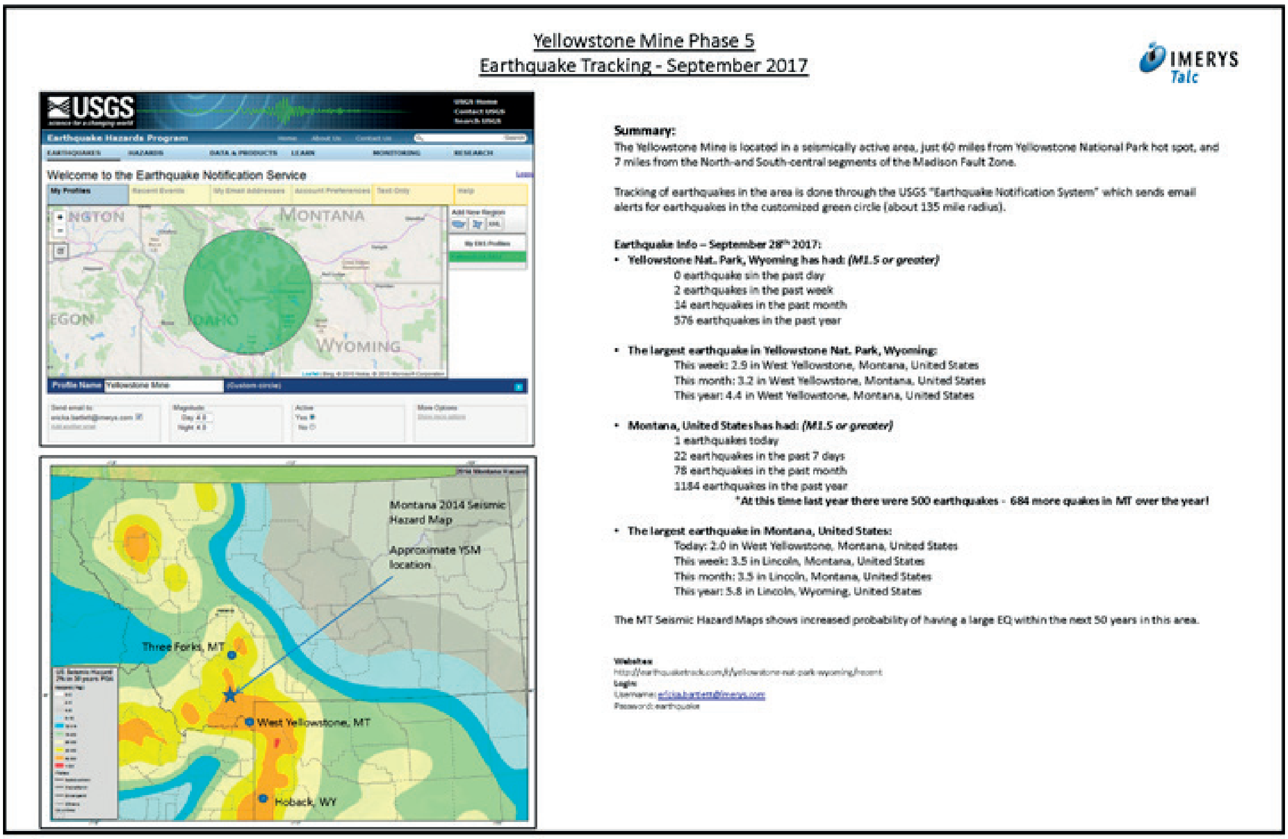


FIGURE 24. Seismic Monitoring

Yellowstone Mine Phase 5
Seismograph Data - September 2017

IMERYS Talc

Summary:

- Plant monitoring for peak particle velocity is done using a Minimate Seismograph. It is located on the footing of plant office building near the entrance to the lab.
  - It continuously monitors all vibrations and frequencies at the plant.
  - Results are reviewed after a blast in Phase 5 and on a monthly basis.
- Blast vibrations to-date have been **below the limit of 2 in/s** at the plant.
- **Seismograph has been returned from calibration. Monitoring resumed on 9/5/2017**

Phase 5 Seismograph Monitoring			
Trigger Level (in/s): 0.03			
Range (in/s): 1.25			
Date	Blast Number	Max PPV (in/s)	Frequency (Hz)
9/7/2017	6075PR01	-	-
9/13/2017	6150 Access Trim	-	-
9/21/2017	6100PR12	0.127	6.8
9/26/2017	5850 Talc	0.112	8.1

*Seismograph was reconnected 9/5/2017

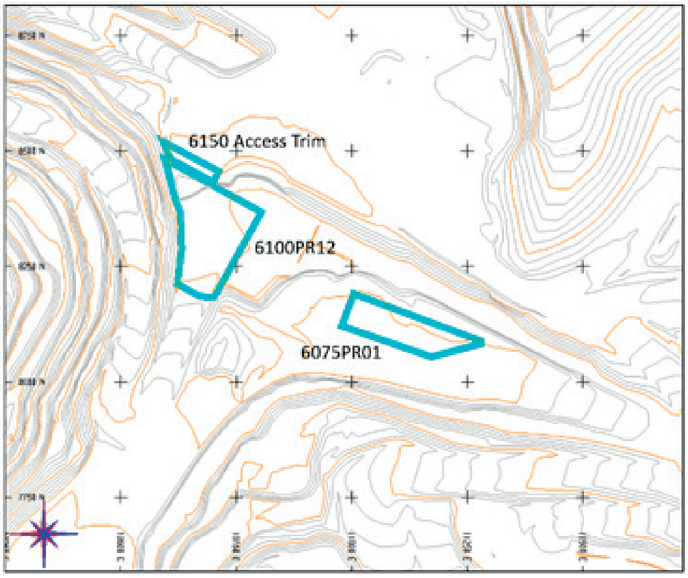


FIGURE 25. Blast Monitoring

CURRENT EXCAVATION PRACTICES

Talc and volcanic units are excavated by dozer and shovel. Pre-split blasting is performed on dolomite slopes resulting in increased bench face angles. A pre-split dolomite bench face is shown in Figure 26.

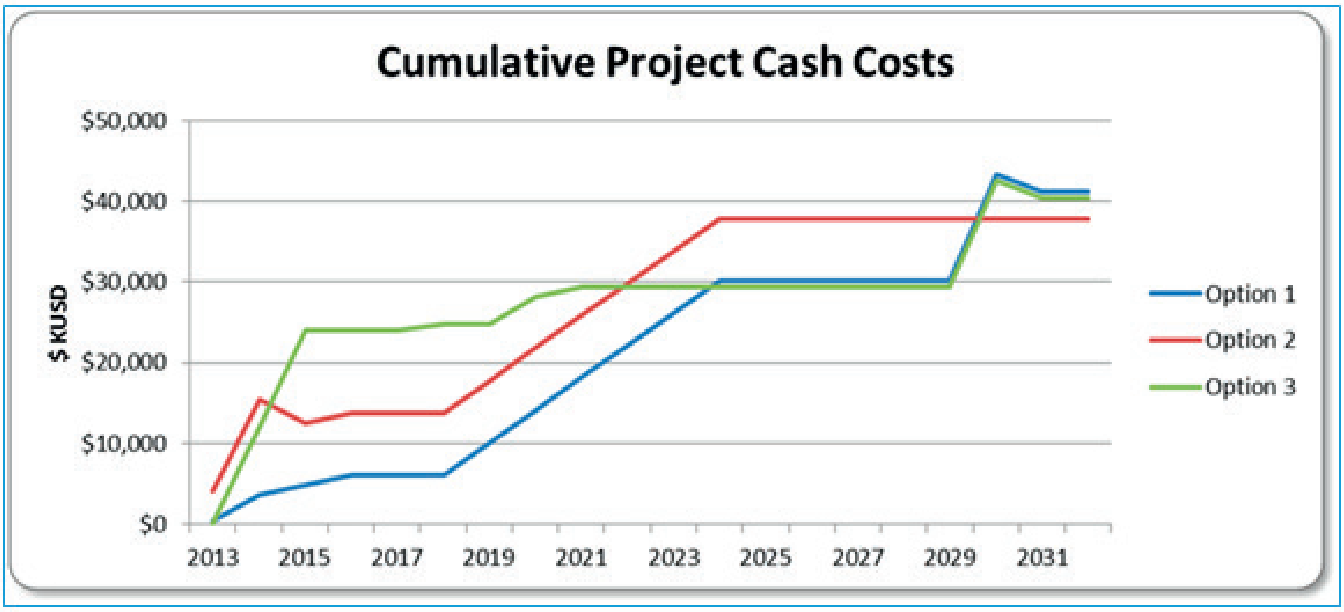
FIGURE 26. Pre-split Blasting in Dolomite Benches

10. COST ANALYSIS

Three options were analyzed for Phase 5, each with varying risk and cash flow timing.

1. Phase 5 pushback, leave plant at current location, increase geotechnical monitoring
2. Relocate the plant, Phase 5 pushback, increase geotechnical monitoring
3. Develop Phase 6 to the north with a higher stripping ratio, then move plant and develop Phase 5

The options and corresponding costs are showing in Figure 27.



Option	Unit mining cost ($/t)	Discounted Cash Cost of Mining	Pros	Cons
1: Phase 5 without relocation	$15.98	-$34.7 million	-Optimized financials -Potential technology improvement	-Geotechnic stability is critical for success -Moderate business continuity risk (managed through monitoring)
2: Phase 5 with relocation	$15.62	-$38.2 million	-Eliminate risk of business discontinuity from slope failure	-High capital expenditure early in plan -New plant built with existing technology
3: Phase 6 before Phase 5	$22.08	-$52.4 million	-Postpone risk of business discontinuity from slope failure	-High overburden required immediately -Geotechnical instability must still be addressed

FIGURE 27. Mining options and Cumulative Costs

After analysis of the reviewed options, Option 1 offered the following benefits:

- Option 1 has the smallest discounted cash cost of mining as the largest expenses are delayed to future years.
- It provides flexibility to develop improved sorting process for a future plant.
- Slope designs have been analyzed and have shown acceptable results by mining standards.
- Identified risks can be mitigated. In the case of a land movement, the construction of the new plant can be expedited while inventory is used to continue supply.

Option 1 (Phase 5 without relocation) was selected as the plan to move forward. Emergency response plans, monitoring programs, trigger action response plans and levels, and contingency plans were developed for implementation prior to Phase 5 overburden removal in 2015.

11. ACKNOWLEDGEMENTS
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